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Mechanical behaviour of thermally activated building structures

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This paper focuses on two low-energy systems – thermo-active building systems and energy foundations – both of which use concrete elements that are already required for structural reasons but which simultaneously work as heat exchangers. The aim of this work was to study the mechanical behaviour of these concrete elements due to the inclusion of polyethylene pipe heat exchangers cast directly into the concrete core and the influence of fluids flowing inside at a moderate temperature. Cylindrical and cubic specimens of two types of concrete (H-25 and H-30) were manufactured in order to study the influence of temperature through compression and pull-out tests and the influence of the embedded pipes in different positions using compression tests. The mechanical properties were found to decrease with an increase in temperature in both concrete types, with a sharper decline in the H-30 specimens. The pipe layout reduced the mechanical resistance of the structural elements regardless of the type of concrete used, with the most damaging position being perpendicular to the load. It is concluded that thermo-active reinforced concrete elements perform best when the polyethylene pipes are placed parallel to the load and the temperature of fluid in the pipes is lower than 70°C.

Notation

E_{max}	maximum strain energy
E_u	ultimate strain energy
F_R	pull-out strength
δ_{max}	maximum displacement
δ_u	ultimate displacement
ε_{max}	maximum strain
ε_u	ultimate strain
σ_{max}	maximum strength

Introduction

Most of the energy used in the building sector is required to maintain constant room temperatures of around 20°C. The conditions for minimum energy consumption might thus be achieved through optimisation of low-temperature heating and high-temperature cooling systems.

The development and applications of low-energy technologies for buildings allow the elimination, or at least reduction, of dependence on electricity or fossil fuels while providing adequate comfort conditions in the built environment. Examples of available low-energy sources are solar thermal heat, geothermal heat or process waste heat as heat in waste water that could also be used to supply a share of the energy demands by way of heat recovery systems. Heat recovery units connected to highly efficient energy systems (such as heat pumps) and surface heating and cooling systems operating at lower temperature levels than conventional units are beneficial and highly effective.

Among these low-energy technologies, the utilisation of slab mass for thermal storage is widely used in building systems in Europe, allowing the use of low-energy cooling or heating sources. Structural element foundations used to provide thermal energy to the overlying building use one of these low-energy sources – shallow geothermal energy – by circulating a heat carrier fluid inside the piles, piled walls or slabs, thus becoming thermo-active foundation elements and acting as heat exchangers with the surrounding soil. In effect, utilisation of the thermal mass of the ground enables a building to store and transfer to the earth unwanted heat in warm weather, and allows heat pumps to warm the building in winter (Laloui and Di Donna, 2013).

Such systems are highly effective when connected to surface heating and cooling systems as thermo-active building systems (Tabs). They increase the efficiency of heat pumps, ground heat exchangers and other systems using renewable energy sources (Kalz *et al.*, 2012). Tabs, implemented as a water-carrying concrete core temperature control mechanism, use the thermal storage capacity of the concrete slabs between each floor in multi-storey buildings to heat and cool in order to provide adequate comfort conditions in the built environment (Basecq *et al.*, 2013; Olesen, 2012).

The impact of thermo-active foundations and Tabs on the mechanical behaviour of the concrete structure can be analysed on three levels – the effect on the ground, the effect on the foundation and the effect on the structural slabs that make up the floors. Studies have been conducted to determine the impact of thermal variations on the ground (Abuel-Naga *et al.*, 2007; Burghignoli *et al.*, 2000; Cekerevac and Laloui, 2004; Hong *et al.*, 2013). The impact of thermal loads on the mechanical response of the geostructure has also been studied, with full-scale tests on piled foundations (Amatya *et al.*, 2012; Bourne-Webb *et al.*, 2009; Brandl, 2006; Kwag and Krarti, 2013; Laloui *et al.*, 2006; McCartney and Murphy, 2012; Suryatriyastuti *et al.*, 2014; Yavari *et al.*, 2014) and on piled walls (Brandl, 2006). Furthermore, small-scale tests have been performed on thermo-active piles (Kalantidou *et al.*, 2012; McCartney and Rosenberg, 2011; Stewart and McCartney, 2012; Wang *et al.*, 2012). In addition, numerical models simulating the behaviour of these structures have also been performed (Alonso *et al.*, 1999; Gens and Alonso, 1998; Olivella *et al.*, 1996).

Although simulation studies have been used to estimate the thermal comfort and energy consumption of Tabs (Lim *et al.*, 2014; Park *et al.*, 2014), a review of the literature revealed no reported studies on the effect of the thermal activation of building slabs on their mechanical behaviour.

Thermo-active slabs contain embedded pipes in which fluids circulate at low–medium temperatures. The behaviour of these slabs when compared with conventional slabs can be modified by the greatest temperature range in which they operate and by the inclusion of pipes.

The study of concrete behaviour subjected to high temperatures began in the 1950s, and the results of initial studies formed the technical basis for recommendations and design guidelines regarding concrete subjected to high temperatures (Abrams, 1971; Malhotra, 1956; Schneider, 1983).

When conventional concrete is exposed to high temperatures, dehydration reactions in the hydrated cement paste are initiated and thermal incompatibility between the paste and aggregates may appear due to their different linear expansion coefficients; eventually, physical–chemical deterioration of the aggregates may occur (Kassir *et al.*, 1996). This results in concrete degradation that is made evident in a loss of mechanical strength. In the temperature ranges in which thermally activated building structures operate, the expected degradation is very small; however, it is necessary to quantify this degradation for the safe design of such structures.

The aim of this work was thus to study the effect of embedded pipes containing fluids flowing at medium temperature in reinforced concrete structures to be used as thermo-active building elements. In order to assess the effects of an increase in temperature and its influence on the mechanical behaviour of concrete, compressive strengths and the anchoring resistance of steel bars in concrete were studied. To evaluate the effect of the inclusion of pipes, specimens with embedded pipes placed at different positions were tested to compression. The results allow an assessment of the design strategy of thermo-active slabs.

Experimental research

Materials

The following materials were used in the experimental part of this work

- four types of cement, according to RC-08 designation (MdF, 2008)
- potable tap water
- siliceous river sand and siliceous gravel (maximum coarse aggregate size 12 mm)
- 24 mm dia. polyethylene pipes.

No cement additions or additives were used; the proportions of the mixes are given in Table 1.

Experimental stages

First, in order to fulfil the objective of this research, the influence of temperature rise was evaluated by studying its effect on the compressive strength of concrete and the anchoring resistance of steel bars. The influence of the addition of polyethylene pipes on the structural behaviour of concrete elements was then studied, through compression tests, for various pipe positions.

To evaluate the effect of temperature, 52 specimens made from two different types of concrete (H-25 and H-30, corresponding to batches 1 and 2) were produced and subjected to four different temperatures (20°C, 40°C, 70°C and 100°C). Half of the specimens were formed in cylindrical moulds (100 mm dia., 200 mm height) and they were used to evaluate concrete compressive strength. The other 26 specimens were prepared in cubic moulds ($100 \times 100 \times 100$ cm^3) with a 10 mm dia. central reinforcement to carry out pull-out tests. The geometric characteristics of the samples comply with the parameters established in UNE-EN 12390-1:2013 (Aenor, 2013). Three identical specimens were manufactured and tested for each case and the arithmetic mean of the three values was used as the strength value. All of the specimens and the temperatures at which the tests were performed are listed in Table 2.

To analyse the effect of the incorporation of pipes, a further 54 specimens were made from two different types of concrete (H-25 (batch 3) and H-30 (batch 4)): 24 specimens were prepared in cylindrical moulds and 30 in cubic moulds. Polyethylene pipes were placed at different positions in these specimens for

	Concrete type				Proportion
	H-25 (batch 1)	H-30 (batch 2)	H-25 (batch 3)	H-30 (batch 4)	
Cement type	CEM II/BL 32·5	CEM II/AL 42·5	CEM IV/B (V) 32·5N	CEM II/AL 42·5R	
Cement: kg	21·00	15·50	15·50	15·50	1·00
Sand: kg	56·28	41·54	41·54	41·54	2·68
Gravel: kg	53·76	39·68	39·68	39·68	2·56
Water: kg	10·71	7·90	6·26	7·90	0·51
Abraham cone test	8·5	9·5	13	10	—

Table 1. Proportion of batches, materials content and results of Abraham cone test

Test temperature: °C	Cylindrical specimens (compressive strength)		Cubic specimens (pull-out strength)	
	Batch 1 (H-25)	Batch 2 (H-30)	Batch 1 (H-25)	Batch 2 (H-30)
20	CS1-H25-20	CM1-H30-20	AS1-H25-20	AM1-H30-20
20	CS2-H25-20	CM2-H30-20	AS2-H25-20	AM2-H30-20
20	CS3- H25-20	CM3- H30-20	AS3- H25-20	AM3- H30-20
40	CS4-H25-40	CM4-H30-40	AS4-H25-40	AM4-H30-40
40	CS5-H25-40	CM5-H30-40	AS5-H25-40	AM5-H30-40
40	CS6-H25-40	CM6-H30-40	AS6-H25-40	AM6-H30-40
70	CS7-H25-70	CM7-H30-70	AS7-H25-70	AM7-H30-70
70	CS8-H25-70	CM8-H30-70	AS8-H25-70	AM8-H30-70
70	CS9-H25-70	CM9-H30-70	AS9-H25-70	AM9-H30-70
100	CS10-H25-100	CM10-H30-100	AS10-H25-100	AM10-H30-100
100	CS11-H25-100	CM11-H30-100	AS11-H25-100	AM11-H30-100
100	CS12-H25-100	CM12-H30-100	AS12-H25-100	AM12-H30-100
Reference	CS13-H25-REF	CM13-H30-REF	AS13-H25-REF	AM13-H30-REF

Table 2. Nomenclature of specimens tested at different temperatures

subsequent compression testing. These specimens are detailed in Table 3.

Experimental research process

The materials were prepared in the proportions detailed in Table 1 for the four batches. Gravel, cement and sand were mixed in a vertical-axis planetary mixer for 2 min to homogenise the mixture. Without stopping the mixer, the amount of water required (excluding that provided by sand) was then added and mixing was continued for a further 3 min. Once each batch was prepared, concrete consistency was tested by means of an Abraham cone and a metal flat steel plate of 850 × 850 mm², according to UNE-EN 12350-2:2009 (Aenor, 2009a).

Moulds for the different specimens were then filled according to UNE-EN 12390-2:2009 (Aenor, 2009b). They were kept at room temperature of 22°C ± 3°C and relative humidity of 60% for 24 h. After this time, the specimens were removed from their moulds and cured in a moist chamber at a temperature of 20°C ± 2°C and relative humidity ≥95% for 28 d.

In the reference specimens used to study the influence of temperature on concrete, a heat sensor was introduced at half the height and in the middle of the section in the cylindrical specimens, and at half the distance between reinforcement and one of the lateral faces in the cubic specimens, in order to evaluate the interior temperature of the concrete during heating. These specimens, once cured, were left to air dry for 1 week at room temperature in the laboratory, so as not to test the specimens at 20°C with a very different humidity from that of the others. The specimens were then placed in a drying heater until they reached temperatures of 40°C,

Cylindrical specimens (compressive strength)		Cubic specimens (compressive strength)	
Batch 3 (H-25)	Batch 4 (H-30)	Batch 3 (H-25)	Batch 4 (H-30)
No pipe (reference)		No pipe (reference)	
THO-1-H25-REF	THO-1-H30-REF	TO-1-H25-REF	TO-1-H30-REF
THO-2-H25-REF	THO-2-H30-REF	TO-2-H25-REF	TO-2-H30-REF
THO-3- H25-REF	THO-3- H30-REF	TO-3- H25-REF	TO-3-H30-REF
Vertically centred		Vertically centred	
THO-4-H25-VC	THO-4-H30-VC	TO-4-H25-V	TO-4-H30-VC
THO-5-H25-VC	THO-5-H30-VC	TO-5-H25-V	TO-5-H30-VC
THO-6- H25-VC	THO-6- H30-VC	TO-6- H25-V	TO-6- H30-VC
Vertically off-centre		TO-7-H25-V	TO-7-H30-VC
THO-7-H25-VD	THO-7-H30-VD	TO-8-H25-V	TO-8-H30-VC
THO-8-H25-VD	THO-8-H30-VD	TO-9-H25-V	TO-9-H30-VC
THO-9- H25-VD	THO-9- H30-VD		
Horizontally centred		Horizontally centred	
THO-10-H25-HC	THO-10-H30-HC	TO-10-H25-H	TO-10-H30-HC
THO-11-H25-HC	THO-11-H30-HC	TO-11-H25-H	TO-11-H30-HC
THO-12- H25-HC	THO-12- H30-HC	TO-12- H25-H	TO-12-H30-HC
		TO-13-H25-H	TO-13-H30-HC
		TO-14-H25-H	TO-14-H30-HC
		TO-15-H25-H	TO-15-H30-HC

Table 3. Nomenclature and characteristics of specimens tested for compressive strength

70°C and 100°C, when fracture tests by compression (according to UNE-EN 12390-3:2009 (Aenor, 2009c)) and pull-out tests were carried out, both in the universal press Ibertest MIB-60/AM.

In each of the cylindrical samples fabricated to study the effect of the incorporation of polyethylene pipes, before concreting, a pipe of 24 mm dia. and 200 mm long was introduced and placed either vertically centred or off-centre, or a pipe of 24 mm dia. and 100 mm long horizontally centred. In the cubic specimens, a 24 mm dia. 100 mm long polyethylene pipe was placed at the centre of the test piece, in either a horizontal or vertical position. Both types of specimens are shown in Figure 1. Once cured, fracture by compression was performed according to UNE-EN 12390-3:2009 (Aenor, 2009c), again in the universal press Ibertest MIB-60/AM.

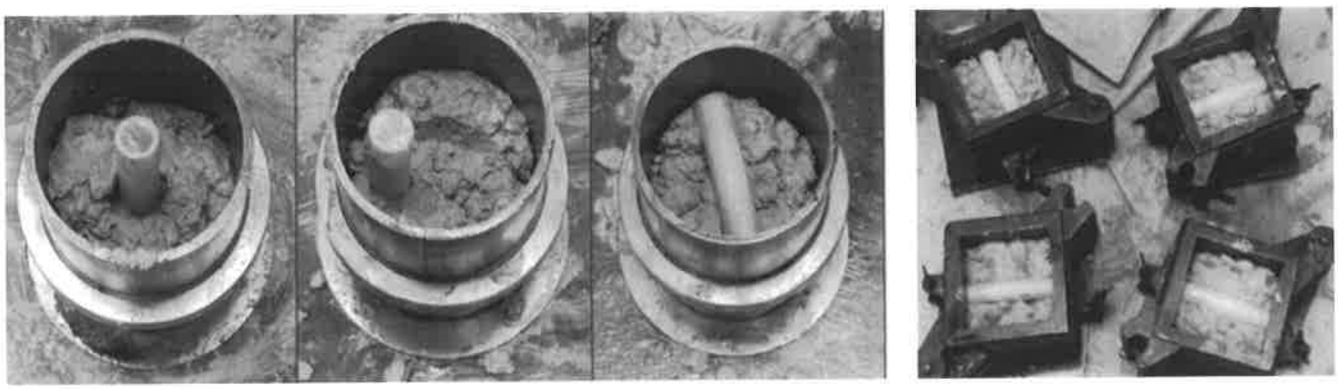

Figure 1. Cylindrical and cubic specimens with 24 mm dia. polyethylene pipes embedded in different positions to test compressive strength

Testing

Compression fracture tests

Fracture by compression tests were carried out according to UNE-EN 12390-3:2009 (Aenor, 2009c). First, the upper faces of the specimens were levelled with sulfur mortar and left in the laboratory for 2 h before testing as per UNE-83506:2004 (Aenor, 2004). Specimens were then placed on the bottom plate of the universal press. A preload of 10% of the maximum load was applied so that the top plate was evenly supported on the upper part of the specimen. Once correctly placed, compression testing was conducted by controlling the displacement, as shown in Figure 2.

Pull-out tests

The pull-out tests were conducted in the same universal press to which two metal plates, joined at the four corners by threaded screws, were added (Figure 3). The lower jaw anchored the specimen in a stable manner and the upper jaw pulled the specimen to test the tensile strength of the 10 mm dia. corrugated reinforcement embedded in the specimen.

Results and analysis

The influence of temperature on concrete is discussed first, using the most representative graphs for each type of specimen. The compressive test results of cylindrical specimens are shown in Figure 4 as plots of strength (σ) evolution against strain (ε) for different test temperatures and the two types of concrete. Regardless of the type of concrete used, the maximum strength decreased with an increase in temperature, with more significant reductions for specimens subjected to temperatures of 70°C or higher.

(a)

(b)

Figure 2. (a) Fracture test by compression of cylindrical specimen subjected to 60°C. (b) Compression test of cubic specimen with embedded polyethylene pipe

Figure 5 shows the results of the pull-out tests for specimens subjected to different temperatures in terms of the evolution of pulling force (F_R) on the displacement (δ). As can be seen, the pulling force decreases with temperature increase, regardless of the type of concrete used.

The most representative graphs for each type of specimen are also used to discuss the influence of polyethylene pipes placed in concrete in different positions. Figure 6 shows the evolution of normal strength and unitary longitudinal strain in cylindrical specimens with polyethylene pipes placed in different positions. As can be seen, for both concrete types, the maximum strength values are similar in the reference specimens and when the pipe is placed in a vertical position, but decrease drastically for a horizontal pipe position.

The results obtained from compression tests on cubic specimens with pipes in different positions are shown in Figure 7. For pipes placed in the vertical position, the maximum strength is lower than in specimens without pipes, but the strength loss is much less significant than when the pipe is placed horizontally.

From the results of the compression tests shown in Figures 4, 6 and 7, the most representative values were selected and calculated; these are maximum strength σ_{max} (calculated using the gross area), maximum strain ε_{max}, ultimate strain ε_u, maximum strain energy E_{max} and ultimate strain energy E_u. In order to compare the results obtained in the tests from different points of view, values obtained from the pull-out tests (Figure 5) were pull-out strength F_R, maximum displacement δ_{max}, ultimate displacement δ_u, maximum strain energy E_{max} and ultimate strain energy E_u. The results are shown in Table 4. The mechanical properties calculated from the compression tests to assess the influence of polyethylene pipes are shown in Table 5.

Discussion

Analysis of the results of the compression tests shown in Table 4 confirms that as the maximum strain increases with the rising temperature in concrete H-25, it decreases in H-30. At the same time, the maximum strain energy and ultimate strain energy do not vary between 20°C and 40°C in concrete H-25, but decrease for 70°C and 100°C. In H-30, the strain energy decreases as temperature increases. Regarding the pull-out tests, the values of maximum and ultimate displacement (δ_{max} and δ_u) decrease dramatically as the temperature rises from 70°C to 100°C, reaching the highest δ_u at 40°C. In addition, the ultimate and

Figure 3. Pull-out testing of cubic specimens

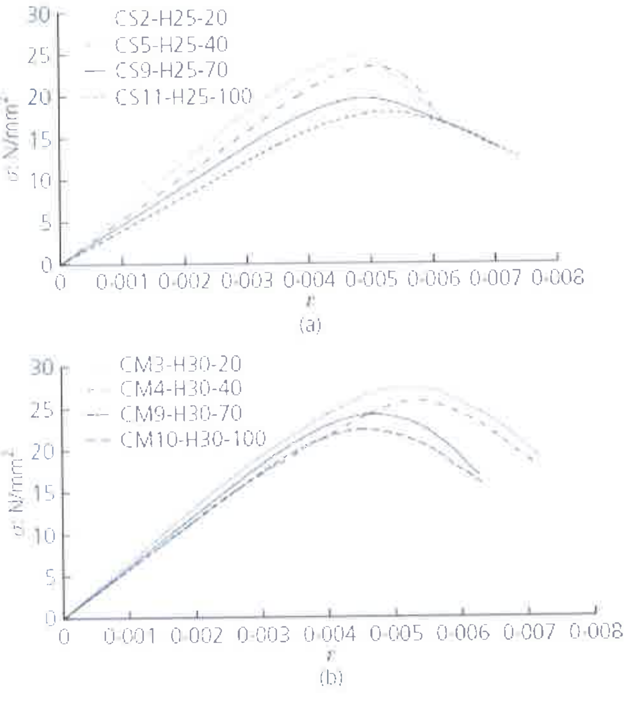

Figure 4. Strength (σ) evolution against strain (ε) in cylindrical specimens at temperatures of 20°C, 40°C, 70°C and 100°C made from (a) H-25 concrete and (b) H-30 concrete

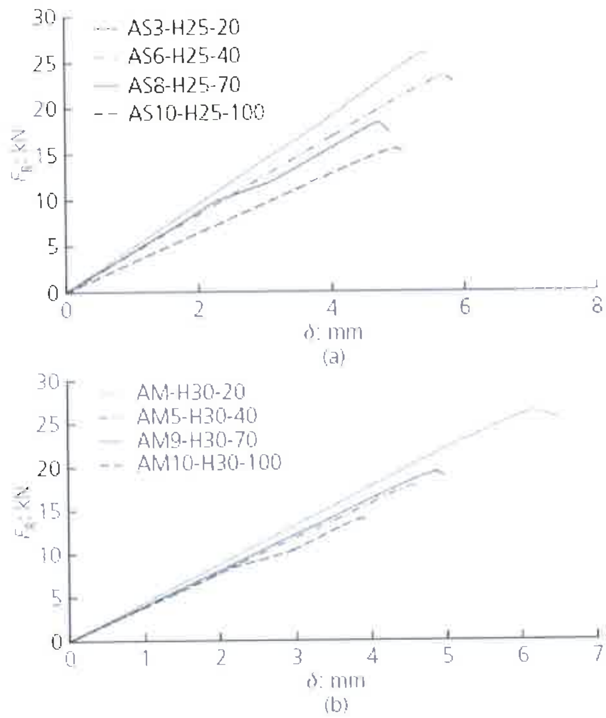

Figure 5. Pull-out strength (F_R) against displacement (δ) in cubic specimens at temperatures of 20°C, 40°C, 70°C and 100°C made with (a) H-25 and (b) H-30

maximum strain energies decrease dramatically when the temperature increases from 70°C to 100°C.

Figure 8 compares the evolution of the maximum characteristic values calculated from compression tests as a function of temperature for the two types of concrete studied. As can be seen, compressive strengths are higher in H-30 concrete than in H-25, although the strengths are closer at a temperature of 100°C. In both concretes the strengths decrease with an increase in temperature. The maximum strain increases as temperature increases in concrete H-25, but decreases in H-30. The maximum strain energy decreases in both types of concrete with an increase in temperature: the increase is fairly constant in H-30, while H-25 concrete shows a much greater increase between 40°C and 70°C.

The correlation between temperature and maximum characteristic values obtained from pull-out tests on cubic specimens of concretes H-25 and H-30 are shown in Figure 9. It can be seen that the maximum pulling force, despite being higher in H-30 concrete, experiences a proportionally greater decrease

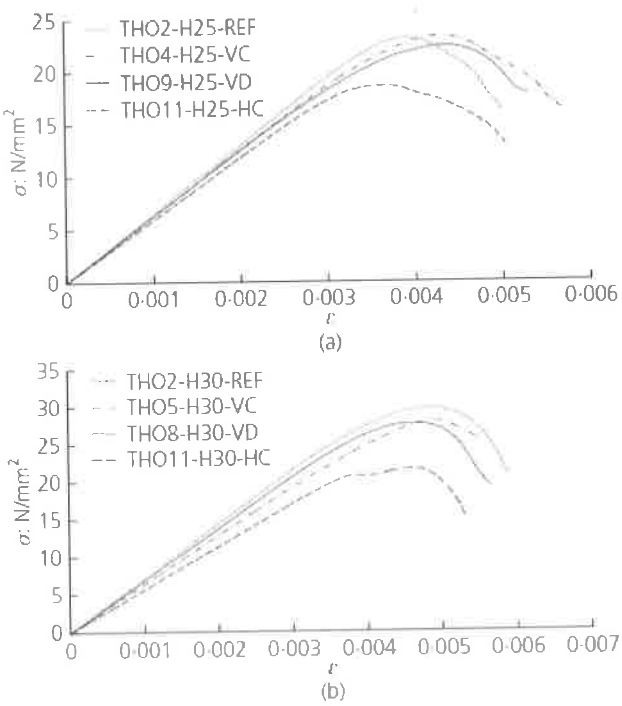

Figure 6. Evolution of strength (σ) against strain (ε) in cylindrical specimens of (a) H-25 and (b) H-30 with no pipe, and with a polyethylene pipe placed vertically centred, vertically off-centre or horizontally centred

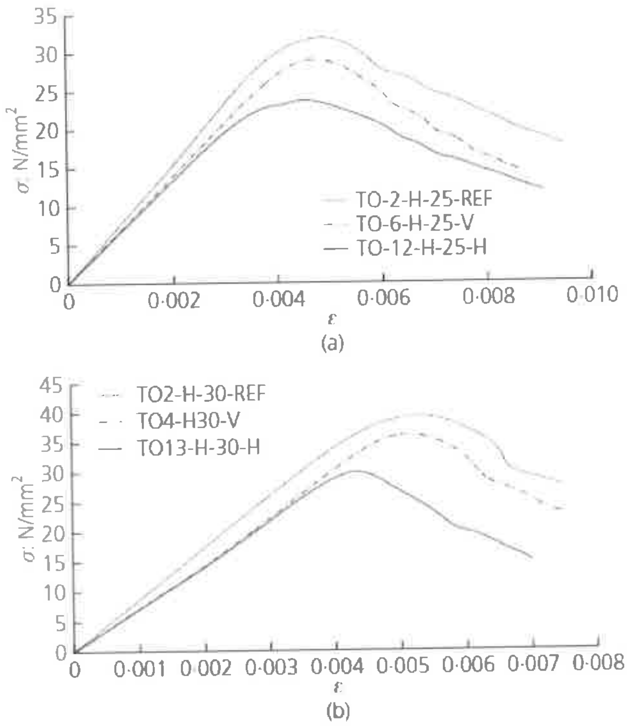

Figure 7. Evolution of strength (σ) against strain (ε) in cubic specimens of (a) H-25 and (b) H-30 with no pipe and with a polyethylene pipe placed vertically centred or horizontally centred

Temperature: °C	Concrete type	Compression tests					Pull-out tests				
		σ_{max}: N/mm²	ε_{max}	ε_u	E_{max}: N/mm²	E_u: N/mm²	F_R: kN	δ_{max}: mm	δ_u: mm	E_{max}: N/mm²	E_u: N/mm²
20	H-25	24·10	0·0049	0·0066	0·0671	0·1016	24·22	5·63	5·78	69·92	73·52
20	H-30	27·70	0·0052	0·0069	0·0827	0·1225	27·42	5·49	5·64	80·35	85·06
40	H-25	22·81	0·0052	0·0069	0·0621	0·0996	21·31	6·74	6·94	72·85	77·07
40	H-30	26·12	0·0053	0·0069	0·0777	0·1169	22·51	5·21	6·35	62·33	73·95
70	H-25	19·51	0·0053	0·0073	0·0566	0·0941	18·37	6·21	6·32	57·58	59·60
70	H-30	24·61	0·0048	0·0061	0·0669	0·0967	18·92	5·95	6·08	53·83	56·22
100	H-25	18·22	0·0055	0·0075	0·0525	0·0908	15·17	4·77	4·89	36·75	38·73
100	H-30	21·40	0·0046	0·0066	0·0560	0·0932	14·52	3·61	3·80	28·50	30·71

Table 4. Mean values of three specimens subjected to each temperature in compression and pull-out tests

than the H-25 concrete does, especially when rising from 20°C to 40°C. The maximum displacement increases for a 40°C temperature and continues to decline as temperature increases, while the performance of concrete H-30 tends to be similar for a 70°C temperature. The maximum strain energy decreases more significantly in the H-30 concrete. Comparing the graphs of the most representative values reveals that the greater slopes (i.e. when the characteristics of concrete decline more significantly) for all the graphs are in the temperature interval from 70°C to 100°C.

Analysis of the data shown in Table 5 indicates that, in the cylindrical specimens, the maximum strains (ε_{max}) are similar in specimens with pipes arranged parallel to the load direction (both

Pipe position	Concrete type	Cylindrical specimens					Cubic specimens				
		σ_{max}: N/mm²	ε_{max}	ε_u	E_{max}: N/mm²	E_u: N/mm²	σ_{max}: N/mm²	ε_{max}	ε_u	E_{max}: N/mm²	E_u: N/mm²
No pipe	H-25	23·22	0·0038	0·0047	0·0472	0·0434	31·98	0·0049	0·0101	0·0878	0·2097
No pipe	H-30	29·91	0·0048	0·0056	0·0806	0·0867	34·62	0·0064	0·0094	0·1156	0·1929
Vertically centred	H-25	22·02	0·0041	0·0051	0·0505	0·0701	27·90	0·0047	0·0091	0·0720	0·1626
Vertically centred	H-30	27·09	0·0046	0·0053	0·0694	0·0546	32·44	0·0053	0·0079	0·1018	0·1330
Vertically offset	H-25	22·42	0·0042	0·0055	0·0534	0·0718	—	—	—	—	—
Vertically offset	H-30	26·77	0·0046	0·0058	0·0702	0·0624	—	—	—	—	—
Horizontally centred	H-25	18·28	0·0034	0·0046	0·0343	0·0531	24·52	0·0042	0·0085	0·0587	0·1369
Horizontally centred	H-30	21·58	0·0044	0·0053	0·0531	0·0597	29·01	0·0045	0·0085	0·0717	0·1282

Table 5. Mean values for one out of three or six similar specimens subjected to compression, made with concretes H-25 and H-30, and with polyethylene pipes in different positions

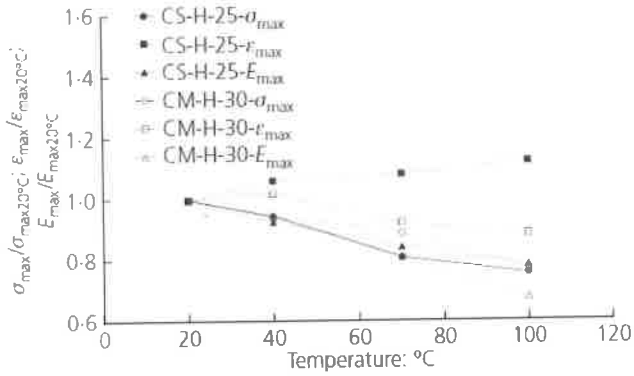

Figure 8. Evolution of maximum characteristic values of compression testing of cylindrical specimens made with concretes H-25 and H-30

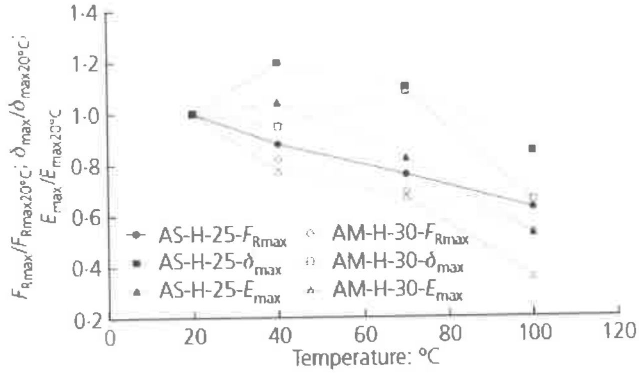

Figure 9. Evolution of maximum characteristic values of pull-out tests with temperature for cubic H-25 and H-30 specimens

centred and off-centre) and decrease when the pipe is laid perpendicular to the load, regardless of the type of concrete. In the cubic specimens, the maximum strains are greater in specimens without pipes, and the lowest values occur for horizontally placed pipes.

Figure 10 compares characteristic compression test values for cylindrical specimens with respect to pipe position for the two types of concrete studied. The strength loss is most noticeable for H-25 specimens with a horizontal pipe. For a vertically laid pipe, the percentage strength loss is similar in both concrete types. The maximum strain is smaller for a horizontal pipe position in the two types of concrete studied. Higher strengths are obtained in specimens without pipes and the smaller strengths are noted when the pipe is laid perpendicular to the load.

Figure 11 shows the correlation of maximum compression test values of cubic specimens for the various pipe layouts in the two types of concrete studied. As can be seen, strength, maximum strain and strain energy are all greater for the pipe in

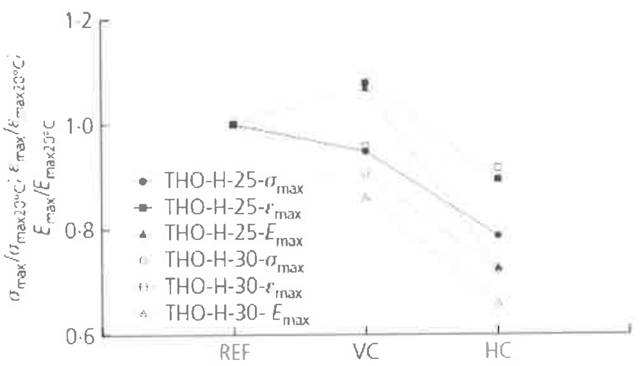

Figure 10. Correlation between maximum characteristic compression test values for different pipe positions in cylindrical H-25 and H-30 specimens

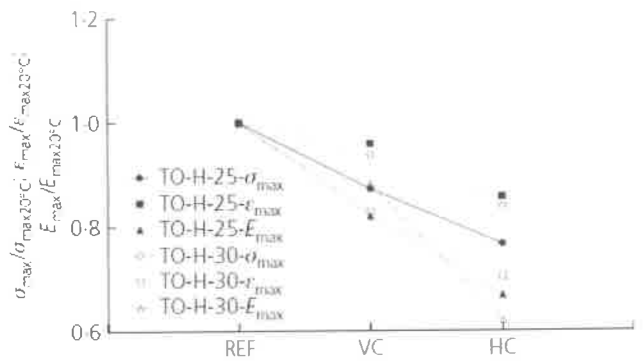

Figure 11. Correlation between maximum characteristic values of compression tests for different pipe positions in H-25 and H-30 cubic specimens

a vertical position and with reinforced concrete H-30. As with the cylindrical specimens, the worst pipe layout is perpendicular to the direction of the load.

Figure 12 compares the values of ultimate strain energy (E_u) depending on the type of concrete, specimen type and pipe layout. As can be seen, E_u is practically linear in the cubic specimens, being higher in H-25 concrete and in specimens without pipes. The ultimate strain energy decreases for a pipe inserted in an upright position and is reduced even more for a horizontal pipe. In the prismatic specimens the behaviour is not so linear, with a higher E_u in H-30 concrete in specimens with no pipe or with the pipe laid horizontally, whereas E_u is greater in specimens made with H-25 concrete and with a vertical pipe. Furthermore, in all cases, E_u is greater in the cubic specimens than in the cylindrical specimens.

Table 6 shows the correlation between strength loss, temperature and pipe position for concretes H-25 and H-30. As can be seen,

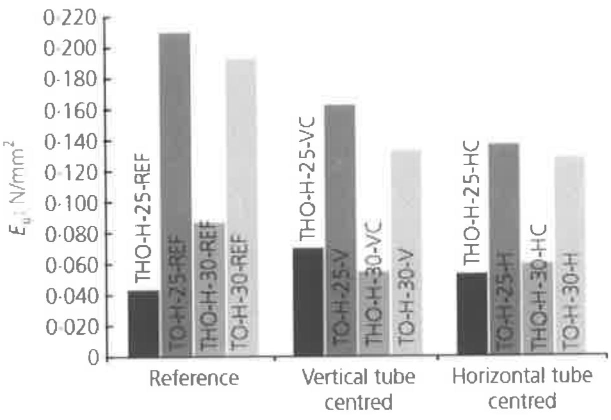

Figure 12. Ultimate energy in cylindrical and cubic specimens of H-25 and H-30 concretes with no pipe and with centred vertical and horizontal pipes

strength losses increase as temperature increases, both in the compression test and the pull-out test, with strength losses of around 20% when H-25 reaches 70°C and when H-30 reaches 100°C. In the pull-out test, the strength loss values are greater at lower temperature in relation to those obtained in the compression test, reaching values above 20% in the two types of concrete at 70°C. The introduction of polyethylene pipes reduces concrete strength in both cylindrical and cubic specimens, with bigger losses (over 20%) for a horizontally laid pipe (i.e. perpendicular to the load).

Conclusions

From the results obtained in the tests and the analysis performed, the following conclusions can be drawn.

- The compressive strength and pull-out strength are higher in concrete specimens made with H-30 rather than H-25.
- Regardless of the type of concrete, an increase in temperature diminishes its mechanical properties.
- The placement of polyethylene pipes inside concrete specimens reduces their mechanical capacity, this reduction being more pronounced for a pipe laid perpendicular to the application of load.

It can thus be concluded that, in thermo-active structures, pipes should be preferably placed parallel to the load and the temperature of the fluid passing through the pipes should be lower than 70°C: as temperature increases, the concrete strength decreases by more than 20%. A thermo-active building structure acts as a high-temperature cooling system (16–20°C) and a low-temperature heating system (25–30°C). The temperature of heat-carrying water in the pipes is always lower than 55°C and therefore it is reasonable to assume that this technology would not jeopardise the mechanical properties of concrete by strength losses of more than 20%.

Temperature: °C	Concrete type	Strength loss: %		Pipe position	Strength loss: %	
		Compression test Cylindrical	Pull-out test Cubic		Compression test Cylindrical	Compression test Cubic
20	H-25	0·00	0·00	No pipe	0·00	0·00
20	H-30	0·00	0·00	No pipe	0·00	0·00
40	H-25	5·35	12·01	Vertically centred	5·17	12·76
40	H-30	5·70	17·91	Vertically centred	9·43	6·37
70	H-25	19·05	24·15	Vertically offset	13·45	—
70	H-30	11·16	31·00	Vertically offset	10·50	—
100	H-25	24·40	37·37	Horizontally centred	21·27	23·33
100	H-30	22·74	47·05	Horizontally centred	27·85	16·20

Table 6. Strength loss in concretes H-25 and H-30 for different concrete temperatures and pipe positions

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